Renewable and Sustainable Energy Reviews 14 (2010) 2748–2759

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Use of crude filtered vegetable oil as a fuel in diesel engines state of the art: Literature review

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ARTICLE INFO

Article history:
Received 12 May 2010
Accepted 16 June 2010

Keywords:
Crude filtered vegetable oil
Biofuels
CI engine

ABSTRACT

Many studies have been published on vegetable oil use in diesel engines. The different authors unanimously acknowledge the potential and merits of this renewable fuel. Typically, Straight Vegetable Oils (SVOs) produced locally on a small scale, have proven to be easy to produce with very little environmental impact. However, as their physico-chemical characteristics differ from those of diesel oil, their use in diesel engines can lead to a certain number of technical problems over time. In bibliography, there is substantial disagreement between authors regarding the advanced phenomena linked to this problems and the recommended solutions. Some of these publications treat options individually without any real comparison between them. Another observation is that the literature rarely tackles problems linked to vegetable oil quality. This paper sets out to review the state of the art for SVO use as fuel in diesel engines, based on a bibliographic study (literature review). The first section of the document examines the influence of the type and quality of vegetable oils for fuel use in diesel engines. The second section discusses the advantages and disadvantages of two options recommended for SVO use in diesel engines: dual fuelling and blending with diesel fuel.

Contents

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doi:10.1016/j.rser.2010.06.018

1. Introduction: vegetable oils as fuel

Growing interest is being shown in biofuels as engine fuels, be it for electricity production, transport or agricultural mechanization in both developing and industrialized countries [1]. There are many reasons for this revival in interest, but the main ones include:

- declining petroleum resources and increasing energy consumption,
- the search for solutions to replace petroleum-based products,
- the virtually global commitment to reduce greenhouse gas emissions (GGE),
- the development of local resources: support to companies and small-scale producers, well-being and added value.

Diesel engines are widely used in the transport, electricity generation and shaft power [2]. These sectors are heavy consumers of petroleum oils which can be partially or totally replaced by vegetable oils and their derivatives which are derived from agriculture and thus of renewable origin [2,3].

1.1. Vegetable oil use as fuel

Using vegetable oils as fuel is not new and dates back to the end of the 19th century with the inventor of the diesel engine [4,5]. In 1900, at the Universal Exhibition in Paris, the OTTO company exhibited a small engine which, at the request of the French government, ran exclusively on groundnut oil [6,7]. The engine, which had initially been designed to run on diesel oils, worked with vegetable oil without any modification.

During World War II, vegetable oils were used to power diesel engines in isolated areas [8]. For example, in the Port of Abidjan (Ivory Coast), where it was becoming difficult to supply conventional fuels, the port construction company powered its 50–800 hp engines with palm oil filtered on a filter press at a rate of 100 tonnes per month [9].

Renewed interest was shown in vegetable oil fuels for engines in the 1970s with the two oil shocks. Very many countries launched research programmes at the time to optimize vegetable oil use as fuel [9].

Many researchers from different countries are still investigating the use of different types of vegetable oils as diesel fuel substitutes [2]. For example, soybean oil is being tested and used in the USA, as are rapeseed oil and sunflower oil in Europe, palm oil in Southeast Asia [2], and cottonseed oil and *Jatropha curcas* oil in West Africa [10,11].

1.2. Challenges for Africa

Developing countries, in West Africa, are in the grips of a financial crisis to which they can see no end, they are underdeveloped in energy terms and are having to deal with their growing food needs [9,12]. One of the major problems lies in African agriculture, which is too outdated, under-mechanized, short of energy and condemned to increase its production to meet its needs. To cope with this challenge, Africa must no longer continue extending its very low-yielding agriculture to new, freshly cleared areas, but rather try to mechanize agricultural work and use high-yielding varieties, while strengthening postharvest treatments and agro-food processing [12]. These are all sectors that consume energy which must absolutely remain available and be protected from fluctuations in diesel fuel prices. In this context, vegetable oils can provide a solution for mechanizing African agriculture.

1.3. Producing vegetable oils for fuel

Vegetable oils can be obtained from oilseed plants (groundnut, rapeseed, castor, *J. curcas*, soybean, sunflower), and from the seeds of plants grown for textile fibres and, secondarily, oil (mainly cotton and flax). As for oil-bearing fruits, they come mostly from coconut palms (coconuts containing copra), walnut trees, oil palms (palm fruits and kernels), and olive trees (olive). Table 1 lists the main vegetable oils and the oil content of their seeds or fruits.

Vegetable oils have physical characteristics close to those of diesel oil (Table 2) and therefore behave like similar fuels. They are also biodegradable, non-toxic and, as they are of plant origin, they have the potential to significantly reduce CO_2 emissions into the atmosphere [14].

1.4. Using vegetable oils as fuel

Vegetable oils are known for their overall performance as fuel (efficiency, emissions, etc.) but also for a certain number of problems encountered in their use [2,14]. Such problems are

Table 1
Vegetable oils used for fuel [13].

Family	Botanical name	Common name	Oil/seed (%)
Monocotylédones			
Palmaceae	*Cocos nucifera*	Coconut	60
Palmaceae	*Elaesis guineensis*	Palm, palm kernel	20 and 50
Palmaceae	*Orbignya eprciosa*	Babassu	60
Dicotylédones			
Juglandaceae	*Juglan regia*	Walnut	50
Cruciferae	*Brassica compestris*	Rapeseed	41
Papilionaceae	*Arachis hypogaeasis*	Groundnut	50
Linaceae	*Linium usitatissimun*	Flax	38
Compositae	*Carthamus tinctorius*	Safflower	35
Euphorbiaceae	*Aleurites fordii*	Tung	60
Euphorbiaceae	*Ricinus communis*	Castor	49
Euphorbiaceae	*Jatropha curcas*	Jatropha curcas	25
Malvaceae	*Gossypium hirsitum*	Cotton	36
Buxaceae	*Simmondsia*	Jojoba	60
Sapotaceae	*Butyrospermum parkii*	Sheanut	30
Pedaliaceae	*Sesamum indicum*	Sesame	52
Compositae	*Heliantus annuus*	Sunflower	40
Papilionaceae	*Glycine max*	Soybean	25

Table 2
Physical characteristics of SVOs [2,9,18,40].

Oil	Density at 20 °C	Flash point (°C)	Cetane number	NCV (kJ/kg)	Kinematic viscosity (mm^2/s)	Pour point (°C)
Diesel	836	93	50	43,800	3–7.5	<−5
Cotton oil	921	243	35–40	36,780	73	−1
Palm	915	280	38–40	36,920	95–106	31
Copra	915	–	40–42	37,100	30–37	20–28
Rapeseed	915	320	32–36	37,400	77	−11
Sunflower	925	316	35–37	37,750	55–61	−5
Soybean	920	330	36–38	37,300	58–63	−4
Groundnut	914	258	39–41	39,330	85	9
Jatropha curcas	920	240	45	38,850	55	3
Flax	940	241	35	39,307	45–50	1.7
Corn	915	277	98	39,500	60–64	−1.1

regularly described in literature: clogged filters, deposits in the combustion chamber [1–3,14–18], etc., and various solutions are proposed:

- blending vegetable oils with diesel oil in different proportions,
- preheating vegetable oils or dual fuelling,
- exhaust gas recirculation (EGR) in the engine,
- modifying the combustion chamber (piston, injector, etc.).

Analysis of publications rapidly reveals differences between authors as to what lies behind these problems and how to deal with them. Another finding is that many publications discuss options separately, without any true comparison between them [2,14,17,19–22].

What the published studies unanimously acknowledge is that if vegetable oils are to be used effectively in a diesel engine, it is important to have oil of good quality but also to make the necessary adjustments to the engine.

1.5. Vegetable oils and Straight Vegetable Oils (SVOs)

The purpose of this study was to review the fuel use of vegetable oils produced on a small scale, usually for local use and within a short, home-use supply chain. These natural vegetable oils, called SVOs, are simply filtered, unlike industrially produced refined vegetable oils.

SVOs offer the advantage of being produced by an easily transferrable simple technology which can even be considered for energy applications in small villages in outlying areas.

The two types of vegetable oil have the same chemical composition but it is the existence of minority compounds (phospholipids, waxes, etc.) in simply filtered oils that differentiate them from industrial refined oils, which contain very little or no such compounds.

SVOs have a chemical composition that corresponds in most cases to a mixture of 95% triglycerides and 5% free fatty acids, sterols, waxes and various impurities [4,9,14,15].

The first section of this paper investigates the effect of the nature and quality of SVOs for use as fuel in diesel engines. The second section, based on a bibliographical study, discusses the advantages and disadvantages of two of the four options recommended for SVO use as fuel in diesel engines: dual fuelling and SVO/diesel oil blends. These two adaptive solutions have the advantage of being the most frequently adopted and simple to use.

2. Section 1: influence of the type and quality of SVOs (straight vegetable oils) for fuel use

In order to certify SVO quality and enable this sector to expand (quality oil sales), it is important for norms and standards to be developed and applied. Draft European standards are proposed today based on petroleum industry methods (ASTM D 6751-02, DIN EN 14214) [14,23,24]. The analytical methodologies proposed are derived from standards initially intended to characterize complex petroleum blends, where the oils are composed of different families of chemicals. This means that the European norms and standards proposed for vegetable oil use as fuel are not adapted to small-scale use, by SMEs or in villages, where state of the art analytical techniques and equipment are not available.

The fuel quality of SVOs depends on the nature of the oil-bearing biomass and the treatment it undergoes. Some parameters are linked to the nature and quality of the biomass used, whereas others are specifically linked to its processing, and depends more particularly on pressing processes. A proper command of these processes is therefore a prerequisite for obtaining a good quality fuel.

Vegetable oil production from seeds or oil crops takes place in three major stages:

- Oilseed storage after harvest,
- Seed crushing,
- Oil processing.

This section describes current knowledge of the way oil quality is affected by the nature of the oil-bearing biomass and by the treatments that oilseeds are subjected to, and proposes ways to optimize it.

2.1. How oil quality is affected by the nature of the oil-bearing biomass

Depending on the nature of the oil-bearing biomass from which SVOs are obtained, and on extraction and drying conditions, they display highly variable physico-chemical characteristics and combustion properties.

2.1.1. Chemical characteristics of SVOs

2.1.1.1. Nature of fatty acids (in this respect, SVOs and industrial oils do not differ). The nature of fatty acids and their contents in vegetable oils depend on the type of oil crop used. The nature of fatty acids largely determines their ability to burn correctly in an engine. Vaïtilingom and Daho found that the unsaturation of triglycerides affected combustibility [9,13].

The iodine value indicates the degree of insaturation of oil (number of double and triple bonds). It corresponds to the number of grams of iodine absorbed by 100 g of fat or oil. The more oil is unsaturated, the higher is its iodine value. A low iodine value (saturated oil) is propitious to good combustion. However, if the iodine value is too low it can lead to cold characteristics unsuitable for “fuel” use [9].

SVOs can be conventionally classed in four major groups according to their iodine value:

- So-called saturated oils: the iodine value is between 5 and 50 (copra, palm kernel oils).
- Mono-unsaturated oils: the iodine value varies between 50 and 100 (groundnut, rapeseed, olive, etc.).
- Di-unsaturated oils: the iodine value varies between 100 and 150 (sunflower, soybean, corn).
- Tri-unsaturated oils: the iodine value is over 150 (flax, tung, etc.).

Generally, from a "quality" viewpoint, saturated oils offer better combustion (short evaporation time, short ignition delay, fewer deposits) than unsaturated oils. Combustion quality decreases with unsaturation. In addition, the nature of the fatty acids in SVOs determines their tendency towards polymerization. This phenomenon, which usually occurs with unsaturated oils, can clog up the racks controlling fuel injection [9].

On the other hand, saturated oils are more viscous at higher temperatures than their unsaturated counterparts. The existence of double bonds in an unsaturated fatty acid makes it more fluid than the corresponding saturated acid and lowers its melting temperature [9,25].

2.1.1.2. Phospholipid content. Phospholipids are undesirable constituents that come from the cell membranes of seeds and kernels. They vary in concentration depending on pressing and filtering techniques. The phosphorus content indicates the presence of phospholipids. This parameter is very important for fuel use. Indeed, phospholipids are responsible for the fouling of valves, combustion chamber and cylinders when straight vegetable oils are used (gumming phenomenon) [26–29]. SVOs have variable phospholipid contents. For example, cold pressing at around 50 °C produces oil with much reduced phosphorus content.

2.1.1.3. Wax content. Waxes are long-chain fatty acid esters and alcohols (up to 46 carbon atoms); they come from the shell of certain seeds or the skin of some fruits (sunflower, olive) [13]. Wax content may vary depending on the origin of the seed and its ripeness, and on the oil extraction temperature [13]. Waxes are soluble when heated, but should be filtered cold. They do not raise any combustion problems, but they are problematic when cold for peripheral items: feed circuit, pump, filter [9,13].

2.1.1.4. Peroxide value. This value is used to assess the oxidation level of an oil [13] and thereby its degree of stability. The more an oil is unsaturated, the more liable it is to oxidation. Oxidation is a basic phenomenon in any oils and fats industry. Chemical alteration of unsaturated fats and oils by oxygen in the air begins with the formation of a peroxide and then by the formation of "fission products". Such fission products result from splitting of the fatty chain at the double bond, which gives a series of short-chain compounds, such as aldehydes and ketones, responsible for the rancid odour of oils and fats. This reaction begins very slowly then accelerates exponentially. Oxygen fixes itself onto fatty chains differently depending on the temperature at which oxidation occurs. Van Grepen (1996) [30] showed that, for some oils, there is a peroxide value range in which the cetane number increases in line with the peroxide value.

2.1.2. Physical characteristics

2.1.2.1. Kinematic viscosity. The viscosity of SVOs is greater than that of diesel oil and increases in line with unsaturation, carbon chain lengths and decrease in temperature. At ambient temperature, the SVOs routinely used have an average viscosity 10–15 times greater than that of diesel oil [9,13,18] (Table 2). Viscosity affects diesel engine operation, notably through a reduction in the maximum injection flow caused by major pressure drop in the injection pump and in the filters, injectors or nozzles, and poor atomization and vaporization, hence incomplete combustion [2,14,16,17,31,32]. Lubrication problems also often occur at low temperature in some injection pumps, resulting in substantial mechanical losses [9,13,17,33–36]. This high viscosity of vegetable oils is attributed to their high molar mass (600–900 g/mol) [18]. Preheating the oil prior to starting up the engine can be a solution [14,20,37]. Another solution consists in mixing the oil with diesel oil [2,4,6,23,24,38] or starting up the motor with pure diesel oil before switching to straight vegetable oil (dual fuelling).

2.1.2.2. Net calorific value (NCV). This determines fuel consumption and largely the amount of heat given off, along with engine performance. The NCV of vegetable oils is lower than that of diesel oil. The difference between the mass NCV of vegetable oils and that of diesel oil is around 10–15% (Table 2) [2,13]. However, given the high density of vegetable oils, their volumetric NCV is only 5–6% less, on average, than that of diesel oil. Combined with the density, the NCV is used to determine the volume flow rate for vegetable oils compared to diesel oil, so as to inject identical energy [25]. The consequences of the low NCV value of SVOs compared to that of diesel oil are around 8% extra consumption of vegetable oil, a drop in engine power and a drop in thermal efficiency [2,3,14,19,31,39,40].

2.1.2.3. Cetane number. This characterizes the time between injection and combustion in a diesel engine. The higher it is, the more flammable is the fuel. The cetane numbers obtained for most vegetable oils are between 29 and 43 as opposed to 45–55 for diesel oil (Table 2). The consequences of the low cetane number for SVOs compared to diesel oil is a difficult start-up when the engine is cold and increased noise (more brutal combustion due to a longer ignition delay) [9].

No satisfactory analysis method exists at the moment to determine correctly the cetane number of high viscosity products such as vegetable oils, as the standardized method has been developed for diesel oil. Consequently, an appropriate analysis method needs to be developed to measure the cetane number of SVOs precisely.

2.1.2.4. Density. SVO density is 10% higher, on average, than that of diesel oil (Table 2). This is not a problem, as such, but it needs to be taken into account to adjust fuel flow rates, for example [9].

2.1.2.5. Flash point. This is the minimum temperature at which the vapours given off by a product, under standardized conditions, ignite when exposed to a flame. This is clearly higher for SVOs than for diesel oils (+100 °C) (Table 2) and its value has no particular direct influence over combustion efficiency or engine performance; it is more a safety parameter for storage. The usual precautions for the storage of petroleum products therefore go beyond what is needed for SVOs [9].

2.2. Impact of production parameters on SVO quality

As shown in Diagram 1, SVOs are obtained following a certain number of processing operations on the oil-bearing biomass. The successive operations require a simple installation consisting of a press, filters and/or decantation tanks, and storage tanks. All impurities have to be removed from the raw material (biomass), which has to be dried before pressing. Once pressed, the oil has to be filtered by one of the following two operations: either decanting in successive tanks, or direct filtering through a filter. For each stage in the production chain, a certain number of factors may

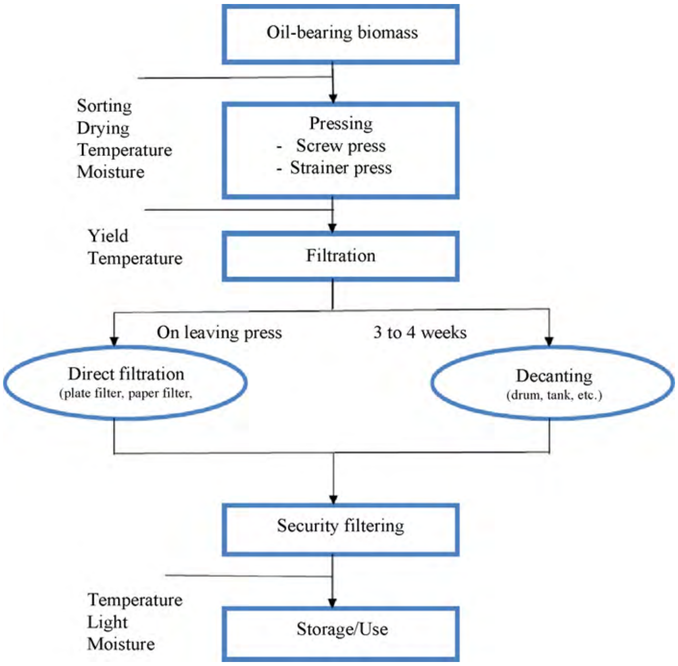

Diagram 1. Technical process for SVO production.

modify or influence the quality of the oil obtained downstream. Consequently, a certain number of precautions have to be taken at each stage of the process.

2.2.1. Oil-bearing biomass quality

Oilseeds come from dedicated crops (*J. curcas*, sunflower, rapeseed, etc.), crop residues (cotton, flax, etc.) or plantations (oil palm, coconut, etc.). Seeds may be stored over several months and they must be free of all impurities. Seeds must be regularly aired to prevent acidification and heat build-up [41]. Batches are considered to be stabilized if their moisture content is 9% in weight or less [42]: this is the maximum seed moisture content for most small-scale presses currently available on the market to operate efficiently. Impurities (leaves, stones, metal objects, etc.) must be removed from seeds and their content must be under 2% [42]. They cause seeds to rot and overheat. In particular, they cause wear in the press, increasing the impurities rate in the oil.

2.2.2. Pressing

Fuel SVO is obtained by simple cold pressing of oil-bearing seeds and fruits. The oils extracted vary in quantity and quality. They especially depend on the type of press, seed variety, moisture content, heating or not, and the cleanliness of the seed [43]. Conventionally, two types of press are available [43]: "hole cylinder or ring" presses for capacities under 100 kg of seeds processed per hour; "strainer" presses, which can be used to press up to 2 tonnes of seeds per hour.

Pressing conditions play a very important role in the quality of the oil obtained. A high relative humidity and a seed temperature below that of the ambient air can cause condensation leading to water in the oil. Preheating seeds to 20 °C helps to improve the extraction rate. The press speed and temperature are important parameters as they directly affect oil quality [42]: the pressing temperature affects the phospholipid content and the speed affects the oil extraction yield. The extraction rate is correlated with press flow. A high flow rate reduces the extraction rate. It is recommended not to exceed a temperature of 80 °C inside the press. The phospholipid content increases proportionally with the extraction temperature, which warrants cold pressing [41,43].

During pressing, it is preferable to opt for continuous press operation to obtain uniform oil and press cake characteristics.

The extraction rate lies within a range of 80–85%. The extent of variations depends on the outside temperature (lower yield in cold weather) and seed moisture content [41,43].

2.2.3. Filtration/purification

Filtration removes all impurities from the oil (heavy particles, metals, phospholipids) for a better quality fuel. Oil purification is an often overlooked, necessary and important step for using vegetable oils sustainably in engines [41,43].

To obtain good quality biofuel SVOs, two techniques are recommended [41,43]:

- Oil decanting, which consists in letting the oil rest for several days, or even a few weeks (3–4 weeks) [41]. Some of the solids (the heaviest) descend by gravity to the bottom of the tank. Decanting should be repeated in successive tanks to maximize efficiency. Decanting is the most economical way to purify oil. However, the process calls for a lot of time and space. Decanting barely achieves the desired level for use as fuel. Final security filtration is therefore recommended after the decanting stage [41,43].
- Direct filtration, which consists in filtering the oil leaving the press through a plate filter press or a vertical filter. Low-temperature direct filtration is not easy because of the high viscosity of SVOs. However, if oil is filtered at too high a temperature, undesirable particles, as for example waxes may pass through the filter. Filtration should therefore be carried out between 20 and 60 °C [41]. Above 60 °C there is also a high risk of oil oxidation, which reduces its shelf life. There are several types of filters, but the plate system is particularly effective in guaranteeing sufficient filtration. When a plate filter is used, direct filtration is recommended without passing through decanting tanks. In addition, when oil is filtered directly after pressing, the outlet temperature of the oil makes filtration easier. In fact, friction inside the press heats the oil to the right temperature for filtration, i.e. around 60 °C. Ideally, filtration should be at 10 μm to prevent any contamination and impurities in the oil [1].

2.2.4. Oil storage

If oils are produced using a small-scale procedure, which is the case with short home-use supply chains, their production is simple and cheap. However, storage is an aspect that requires quality and cleanness (clean containers reserved solely for vegetable oil). The following parameters must be taken into account to guarantee optimum oil storage [43]:

- the oil must be as clean as possible,
- the storage area must be cool,
- temperature variations must be avoided as they lead to condensation,
- the oil must be kept in the dark, sheltered from direct sunlight. Light is conducive to oil oxidation and acidity.

Inappropriate storage conditions over a long period cause oil oxidation, hence higher viscosity and filtration problems in the engine.

2.3. Vegetable oil standard and standardization for fuel use

The strong development of the SVO sector worldwide calls for these new dynamics to be channelled from the outset, by drawing up precise and compulsory specifications adapted to the supply chain from plantation to end user, with transparency and

Table 3
German pre-standard DIN 51605 for SVO production (rapeseed oil).

Properties/content	Unit	Extreme values	
		Min	Max
Acidity	mg KOH/g	–	2
Particle content	mg/kg	–	24
Phosphorus content	mg/kg	–	12
Ash content	mg/kg	–	10
Moisture content	mg/kg	–	75
Calcium and magnesium content	mg/kg	–	20
Oxidation stability (110 °C)	h	6	–
Iodine content	g iodine/100 g	95	125
Sulphur content	mg/kg	–	10
Density (15 °C)	kg/m^3	900	930
Self-ignition point	°C	220	–
Kinematic viscosity (40 °C)	mm^2/s	–	36
Net calorific value	kJ/kg	36,000	–
Flammability	–	39	
Residual carbon	mg/kg	–	400

traceability: a quality norm or standard. A pre-standard from Europe of German origin, exists today for SVO fuel use: DIN 51 605 (Table 3). These recommendations mostly apply to rapeseed oil [44].

This standard is too drastic and involves analytical tools that are difficult to set in place in agricultural zones, especially in developing countries. It is also based on analytical methods used in the petroleum sector that require many resources and technical skills.

Not all the parameters proposed by the standard have to be systematically analysed in SVO production, as many of them comply with the standard by their very nature. SVO should be analysed using at least the factors listed in Table 4.

Several properties, such as density, NCV, kinematic viscosity, etc. do not depend on the processes used to obtain SVO and only depend on the nature of the original biomass. However, the particle, phosphorus, ash and water contents, etc. depend on the strictness of the seed drying, extraction, filtration and oil storage processes. Vaïtilingom (2006) [1] showed in his work that a phosphorus content of 50 ppm in vegetable oil is enough to have the qualities required for fuel use.

The production of SVO as fuel can be envisaged with small-scale tools or industrial tools existing in the food sector. Quality demands are less strict and cheaper than in food production and mostly concern pressing, filtering and storage.

2.4. Summing up on SVO quality

This paper brings out two types of factors affecting the ultimate quality of SVOs:

- Production factors, including storage conditions, seed quality and moisture content, ambient temperature, seed preparation conditions prior to pressing (cleaning, sorting, any preheating, drying, flattening, etc.), extraction (which must be carried out with a minimum of shear and at the lowest temperature possible), but also and predominantly, filtration conditions and quality (equipment, procedures, etc.).
- Factors linked to the nature of the oil-bearing biomass, including the fatty acid, phospholipids and wax contents.

Table 4
SVOs parameters to be analysed for fuel application.

Properties/content	Units	Max	Analysis method
Particle content	mg/kg	24 (24 ppm)	DIN EN 12662
Acidity	mg KOH/g	2.0	DIN EN 14104
Phosphorus content	mg/kg	12 (12 ppm)	DIN EN 14107
Ca and Mg content	mg/kg	20 (20 ppm)	DIN EN 14538
Moisture content	wt%	0.075 (750 ppm)	DIN EN ISO 12937
Wax content			Gas chromatography
Total		100 (100 ppm)	
Crystallisable		75 (75 ppm)	

After filtration, the fuel quality of an oil must be as follows [1]: it must not contain more than 50 ppm of phosphorus and more than 500 ppm of waxes.

Consequently, the following parameters must be mastered during the different operations (drying, pressing, filtration, storage):

- Seed moisture content must be below 9%.
- Seeds must be cold pressed.
- Oil must be filtered to 10 μm or less.
- Oil should be stored away from light, moisture and temperature variations.

3. Part 2: SVO use in dual fuelling and blends with diesel oil

Straight or refined vegetable oils cannot be used directly in direct-injection diesel engines. When such engines deliver up to half their nominal power, they have average chamber temperatures below 200 °C. However, vegetable oil has a much higher flash point than diesel oil: 240 °C for Jatropha oil as opposed to 93 °C for diesel oil. This means that some of the oil droplets will not be vaporized but will stick to the walls, resulting in tar deposits. Such deposits soon accumulate on the injector nose, disrupting spraying and resulting in poorer functioning. They also lodge in the top ring piston throat, preventing flexibility and causing jamming and/or rapid wear of the ring. There is loss of pressure, problems with cold start-up and deterioration in performance (abnormal increase in consumption). If the dilution of vegetable oil in the lubricant then exceeds 1% it can lead to rapid polymerization of the lubricating oil causing the engine to seize up totally due to the absence of lubrication.

In indirect-injection diesel engines with a swirl chamber, the average temperature in the pre-chamber is around 500–600 °C right from 10% of brake power [9]. Vegetable oils burn completely.

As direct-injection diesel engines are the most widely used to produce shaft power and electricity, and in rural applications, it seems more appropriate to investigate their operation with SVO as fuel, even though such engines present more problems when vegetable oil is used.

3.1. General

Vegetable oils are used as fuels in different forms (pure or processed) with or without adapting the engine. Their overall performance as a fuel, along with the many problems encountered when using them, have been widely documented [1–3,5,8,10,13–22,31,32,34,36,37,39,40,45–52].

One of the main problems hindering routine use of natural vegetable oils in modern diesel engines is high heat-sensitive viscosity [29,33,36,53], due to glycerine, which complicates circulation (pumping), filtering and especially the very fine atomization of the injected fuel. The viscosity of SVOs is not alone in causing problems. Once it is overcome, problems still remain but to a lesser extent [54].

Among the studies undertaken and published on understanding and solving these problems, there are many disagreements. This section, which is far from exhaustive, discusses and compares the SVO uses described in the literature. We focus on the main two ways SVOs are used:

- direct SVO use,
- SVO use in blends at different proportions in diesel oil.

3.2. Direct SVO use in an engine through dual fuelling

Straight vegetable oils are used in direct-injection and indirect-injection (pre-chamber) diesel internal combustion engines. Their direct use without modifying the diesel engine results in the problems already mentioned. These problems are linked to the physico-chemical characteristics of vegetable oils and vary depending on the type of engine used.

The authors of publications on direct SVO use unanimously recommend operating in "dual fuelling" [55]. Duel fuelling consists in starting up the engine with diesel oil, then only injecting vegetable oil into the circuit once the engine load is sufficient to give a high temperature in the combustion chamber (500 °C in average), enabling total oil combustion [9].

This procedure has been installed and used by CIRAD on tractors, trucks and electricity generating sets [55].

It consists in installing a second feed circuit for straight vegetable oil in parallel with the diesel circuit (Diagram 2). The circuit comprises the following in series:

- a fuel filter adapted to vegetable oil,
- a heater to reduce oil viscosity and approach that of diesel oil,
- a booster pump,
- a solenoid valve to switch between fuels, i.e. enabling the engine to work on diesel oil or SVO.

The diesel/vegetable oil switch-over is controlled as follows: so long as the combustion chamber has not reached a sufficient temperature for effective vegetable oil combustion, the engine continues to be fed with diesel oil. As soon as the chamber temperature is sufficient, the switch system controls the solenoid valve, which then feeds the engine via the vegetable oil circuit.

Before the engine is switched off, it is run once more on diesel fuel to clear all the vegetable oil from the fuel feed circuit, ready for the next cold start-up with 100% diesel oil.

The switch system can be operated by controlling the following two parameters: the exhaust temperature and the engine rotation speed.

3.2.1. Exhaust temperature

The exhaust gas temperature is proportional to the average temperature of the combustion chambers. It can be measured by placing a probe at the exhaust outlet port in the gas flow [55].

3.2.2. Engine rotation speed

This is measured by rotation sensors connected to the automatic switch system. It should be noted that for constant speed applications (electricity generating sets, some pumping sets, etc.) this sensor is pointless. The speed value is directly programmed as a constant in the switch system [55].

According to literature, dual fuelling offers many advantages:

- the oil is preheated and is therefore more fluid (with a lower viscosity),
- better vaporization in the combustion chamber,
- this solution is compatible with virtually all diesel engines (direct or indirect injection),
- modifications are minor and enable 100% diesel oil use at any time,
- and lastly, the engine is stopped with diesel oil, meaning that the feed circuit is well cleaned.

3.2.2.1. Performance of direct SVO use.

3.2.2.1.1. Torque and power. There are many and different results from studies on vegetable oil use in engines [1–3,8,13,14,17–20,22,25,31,34–36,38–40,45,47–51,53,54,56,57]. In some cases, an approximate 10% drop in power was found with vegetable oils

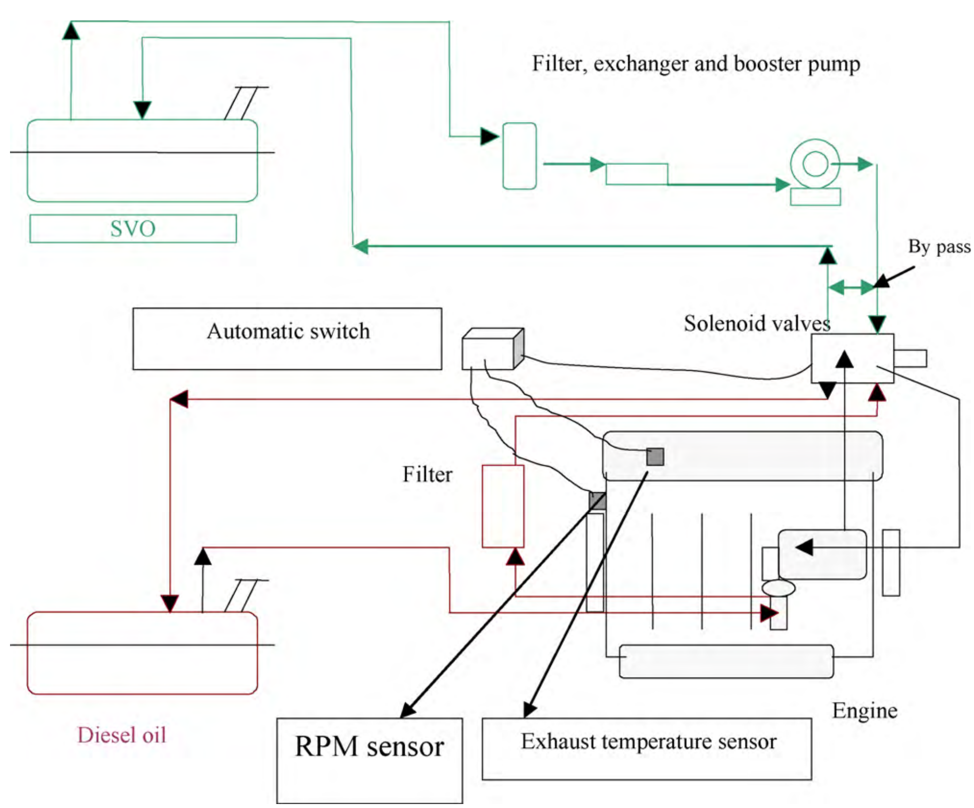

Diagram 2. Modification to feed circuit: example of Cirad dual circuit option [55].

compared to diesel oil [13,19,57]. The authors of these publications attributed that to the lower NCV of vegetable oils compared to diesel oil. On the other hand, some authors have shown that power and torque remain unchanged, often with a 5–10% increase in engine power with vegetable oils compared to diesel oil if minor modifications are made to the engine (injection advance, increased injection pressure, engine supercharging, adaptation of the fuel filter, etc.) [1]. When the corresponding tests are examined in detail, it can be seen that the differences in results can be explained by differences in the type of engine used, the operating conditions and the nature of the oils. Indeed, the researchers used engines with different technical characteristics (stroke, bore, cubic capacity, compression ratio, etc.) and applied different test conditions (test bench, ambient temperature, test instruments, etc.).

3.2.2.1.2. Specific consumption. Specific fuel consumption is an important engine parameter. It defines consumption by unit of power and unit of time. Specific consumption generally decreases with the increase in engine load for all fuels and is higher with SVO than with diesel oil in diesel engines (all publications) given the higher volume consumption [1,8,13,14,17,19,34,39,54,57]. Overconsumption can reach 8% [19] but can be much lower (>5%) according to some authors [2,17,39]. The high specific consumption value for vegetable oils is attributed to their low NCV, high density and high viscosity compared to diesel oil [21,39,40].

3.2.2.1.3. Overall efficiency (thermal efficiency). The thermal efficiency of SVOs as fuel is lower than diesel oil one [39]. The low thermal efficiency with vegetable oils may be due to weak combustion characteristics resulting from their high viscosity and low volatility [14,39]. However, once the engine has been modified, thermal efficiency is relatively higher for vegetable oils than for diesel oil [1].

3.2.2.1.4. Combustion. The ignition delay is the time lapse between the start of injection and the start of combustion. It is the preparation time for the air/fuel mixture prior to combustion. The ignition delays of vegetable oils are longer than for diesel oil, as shown in Fig. 1. This is due to their lower cetane numbers [9,16,57]. However, the differences between vegetable oil and diesel oil ignition delays are not very great, while the difference between cetane numbers is often substantial. Fort et al. [58], like Jalinier [59] published work in the 1980s in which they found that the ignition delay of vegetable oils was shorter than for diesel oil. These disagreements in the results may be due to the conditions under which ignition delays were determined. Vaïtilingom (1992) [9] showed that, with an air inlet temperature of 100 °C, vegetable oils have the same ignition delays as diesel oil, and at 500 °C ambient temperature the same evaporation characteristics as diesel oil.

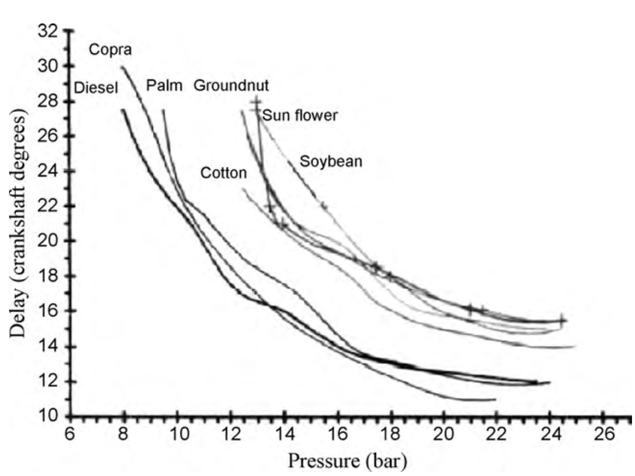

Fig. 1. Ignition delay depending on pressure at the start of injection for diesel oil and 6 vegetable oils, air inlet temperature T_a = 25 °C [9].

3.2.2.2. Exhaust gas emissions. The exhaust gas emissions of SVOs used as fuel compared to diesel oil receive most attention in the literature. Pollutant emissions are classed in two categories: conventional pollutants regulated worldwide since 1970, and specific pollutants whose emission levels are low but attract particular attention given their toxic nature or their harmful environmental effects.

3.2.2.2.1. Carbon monoxide (CO) emission. CO emission from diesel engines is mostly due to heterogeneity of the richness in the cylinders and partial oxidation of hydrocarbons in the exhaust manifold [10].

CO emission is higher with vegetable oils than with diesel oil and it decreases as the engine load increases. CO emission reaches its minimum value at around 75% of the maximum engine load. At that load, the difference is 31.6% [17] between diesel oil and SVO CO emissions. Beyond that load, CO emissions increase up to the maximum engine load [13,14,17,19,57,60]. The reason given is the poor combustion of vegetable oils, which is due to their higher viscosity and low volatility. Other authors have found CO emissions for vegetable oils that were comparable to, if not less than, those of diesel oil, provided the vegetable oils were heated [20,21] or the injection advance was adjusted [20,37]. These last results clearly confirm the effect of atomization and the quality of the air/fuel mixture.

3.2.2.2.2. Carbon dioxide (CO_2) emission. CO_2 emitted from diesel engines running with SVO does not add to greenhouse gases in the atmosphere as it is absorbed by plant growth in the following crop cycle. CO_2 emission from vegetable oils is around 20% higher than from diesel oil due to poor SVO combustion [14]. Other publications give a CO_2 emission from engines running with SVO 6% lower than for diesel oil at an 80% engine load [17]. However, the problem in this case is that the performance of the engine was particularly poor, even with diesel oil.

3.2.2.2.3. Nitrogen oxides emission. Nitrogen oxides, commonly called NO_x, correspond in fact to a mixture of NO and NO_2. Only NO is formed in large quantities under engine operating conditions [13].

NO_x emissions are often lower with industrial vegetable oils or with SVOs compared to diesel oil [1,13,14,17,19,40]. At a 100% engine load, the reduction in emissions reaches 40.3% [17]. The lower NO_x emissions for vegetable oils than for diesel oil are due to the low NCV of vegetable oils [2,17], with lower temperature peaks in the combustion chamber [48,49]. However, some researchers have found an increase in NO_x emissions with vegetable oils compared to diesel oil [20,21]. They attributed their NO_x emissions to the formation of deposits in the combustion chamber, causing a higher temperature inside the chamber. However, all publications acknowledge that NO_x emissions increase in line with engine load (higher temperature).

3.2.2.2.4. Unburnt hydrocarbon emission. By unburnt hydrocarbons (HC) we mean hydrocarbon compounds from the fuel which are found in the exhaust gases, comprising actual carbon and products resulting from complex reactions. In general, HC emissions are greater with vegetable oils than with diesel oil [1,17,40]. This is attributed to the low NCV values for vegetable oils [2,17] and flame extinction at various places (walls, dead volumes, etc.) and the existence of zones too rich in fuel (poor fuel atomization).

However, some studies conducted with well-adjusted engines [21,48,57] have revealed lower unburnt hydrocarbon emissions with vegetable oils than with diesel oil.

3.2.2.2.5. Sulphur dioxide (SO_2) emission. As the sulphur content of SVOs is very low, an analysis of SO_2 emissions is insignificant compared to those for diesel oil [9,13].

3.2.2.3. Deposit formation. Under certain conditions, direct use of vegetable oil as fuel in diesel internal combustion engines leads to the formation of deposits on injector noses, the wall of the combustion chamber and the piston head. Such observations are reported in most studies carried out inside the engine [9,25,34,40]. Only a few studies specify the operating conditions under which the deposits were observed [9,25]. Deposit formation begins on the injector nose, which is the coldest part of the combustion chamber, followed by the rings and the throat, the chamber walls, then the cylinder head, etc.

The intensity of the deposits depends on the type of engine and the quality of the SVO. Deposits are particularly noticeable with direct-injection engines. The temperature level in such engines is low compared to indirect-injection engines.

There are many hypotheses for deposit formation, based on the physico-chemical characteristics of oils and the temperature level in the combustion chamber.

- The physical characteristics implicated in deposit formation are the high viscosity and low volatility of SVOs. In the literature, many authors opt for viscosity as the main cause of deposit formation [40,56,57,61]. The high viscosity of vegetable oils leads to filter clogging, causes poor atomization and high fuel spray penetration. On the other hand, other authors have found that solving the viscosity problem, notably by preheating, reduces the deposit [9]. Solving the viscosity problem results in good atomization and improves combustion, though without settling the problem of deposits. Consequently, this in itself is not enough to prevent deposits from forming. The low volatility of vegetable oil makes its vaporization difficult and incomplete. Oil droplets on the cold walls, following strong penetration, lead to deposit formation as a result of thermal decomposition [13]. The thermal decomposition of vegetable oils depending on temperature has led some authors to conclude that a high temperature would seem to cause deposits [13]. Yet other studies claim that deposit formation disappears with a combustion chamber temperature over 500 °C [9,25,34].
- Chemical characteristics of vegetable oils: deposits are often attributed to the actual chemical nature of oils, notably triglycerides, and the degree of oil processing. In fact, an esterified oil with traces of triglycerides causes deposits, whereas an esterified oil not containing any trace of triglycerides has the same low level of deposits as diesel oil [9,25,34].

The degree to which oil is processed may have a major effect on deposit formation. In fact, the mucilages contained in certain crude oils contribute to deposit formation. During oil refining or simple degumming operations, such mucilage are largely removed. However, mucilage elimination does not prevent deposit formation in some cases. Other parameters relative to the degree of oil processing, such as impurities, ash and soap contents, and acidity have no established correlation with deposit formation. Thus, the effect of oil processing would seem mostly to concern the role played by mucilage [9].

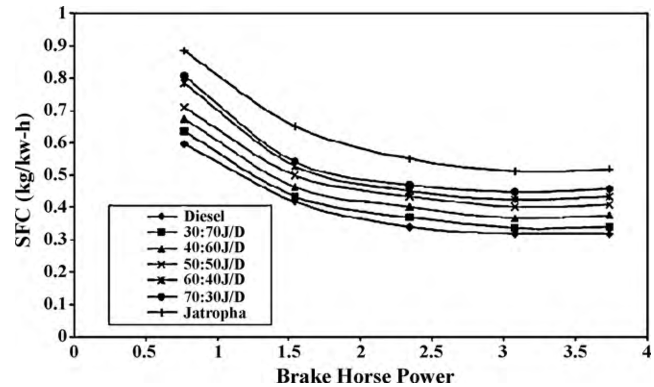

Fig. 2. Specific consumption for pure diesel oil, *Jatropha* and blends [39].

3.3. SVO/diesel oil blends

The high viscosity of SVOs compared to diesel oil is the main cause reported in the literature for the problems encountered in engines. High SVO viscosity results in poor fuel atomization, incomplete combustion, deposits in the combustion chamber and SVO mixing with the lubrication oil. There are several ways to reduce SVO viscosity, and mixing with diesel oil is one of them.

3.3.1. Physical properties of the blend

Table 5 shows an example of the physical characteristics of a blend of *Jatropha* oil and diesel oil in different proportions [39]. In general, the higher viscosity and density of SVOs decrease as the proportion of oil in the SVO/diesel oil blend diminishes. NCV decreases in line with the amount of vegetable oil in the blend.

3.3.2. Comparative performances

Trials conducted with less than 30% straight vegetable oil in the blend gave good performance results comparable to those for diesel oil [2,13,14,17,21,39].

Specific consumption increases as the proportion of vegetable oil in the blend increases, as shown in Fig. 2, due to a higher injected mass of blend [13]. The difference in specific consumption between the blends and diesel oil is maximum at moderate engine loads (50–75%). According to Agarwal and Agarwal (2007) the reason for that increase in specific consumption is due to the lower NCV of SVOs compared to diesel oil [14].

The effective efficiencies are slightly lower as the proportion of vegetable oil in the blend increases (Fig. 3). The thermal efficiency values for SVO/diesel oil blends fall between those for SVO and diesel oil. The general finding is that effective efficiency values remain similar for all the fuels [14,17,22].

Table 5
Physical characteristics of *J. curcas*/diesel oil blends [39].

% of *J. curcas* oil (v/v)	% of diesel fuel (v/v)	Density (g/cm^3), 30 °C	Viscosity (cSt), 30 °C	Viscosity reduction (%)	Observation
70	30	0.900	23.447	55.56	Stable mixture
60	40	0.890	19.222	62.13	Stable mixture
50	50	0.853	17.481	66.86	Stable mixture
40	60	0.880	13.953	73.55	Stable mixture
30	70	0.871	9.848	81.00	Stable mixture
20	80	0.862	6.931	86.86	Stable mixture

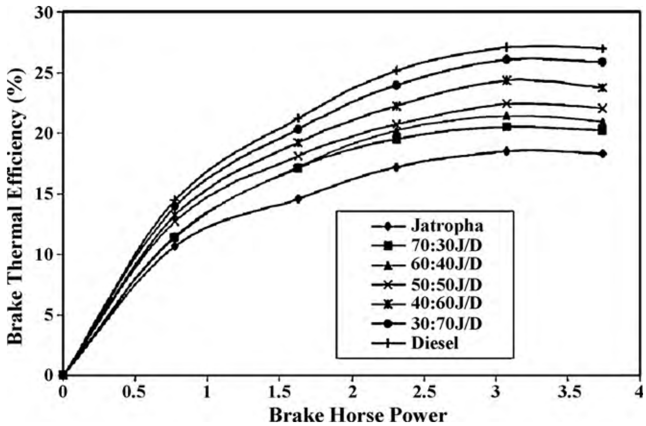

Fig. 3. Break thermal efficiency for different fuels [39].

3.3.3. Pollutant emissions

3.3.3.1. Carbon monoxide (CO). The CO emission results for the different fuels (SVO, SVO/diesel oil blend and pure diesel oil) are within the same value ranges [13]. Emissions decrease as the load increases up to intermediate loads (60–80%). Emissions then increase up to the maximum load.

CO emissions for SVO/diesel oil blends fall between those for SVOs and diesel oil. They rise as the proportion of vegetable oil in the blend increases [13,14,17,22].

3.3.3.2. Nitrogen oxides (NO_x). NO_x emission for vegetable oils and their blends is lower than for diesel oil (all publications) [14,17,22]. This is due to the lower temperature level in the combustion chamber for vegetable oils and blends.

3.3.3.3. Unburnt hydrocarbons (HC). According to studies by Nwafor and Rice (1996) and Kalam et al. (2003), unburnt hydrocarbon (HC) emissions for SVOs and blends are low compared to pure diesel oils [21,22]. Other studies find an increase in unburnt hydrocarbon emissions compared to pure diesel oil [14]. Yet others find no clear tendency for unburnt hydrocarbon emissions [17]. One of the possible reasons for the differences in these results may be the type of engine used (direct or indirect injection).

3.3.3.4. Carbon dioxide emission (CO_2). Carbon dioxide emissions for blends are comparable to or higher than those of pure diesel oil [14,19,22]. Studies by Wang et al. (2006) showed that CO_2 emissions were higher for pure diesel oil compared to blends. The author explained that result through the existence of oxygen contained in vegetable oil molecules [17].

3.3.4. Endurance

According to a bibliographic study by Daho (2008) [13], the endurance of blends with diesel oil remains the same as for straight vegetable oils in indirect-injection engines. With direct-injection engines, blends containing less than 20% vegetable oil perform exactly like diesel oil. However, some authors have found deposits in the combustion chamber with low vegetable oil contents in the blend, but the deposits took longer to form [13].

3.4. Overview of SVO use as fuel in diesel engines

3.4.1. Differences between published results

Many results have been published on the performance and pollutant emissions resulting from SVO use as fuel. We found disagreements in the published results, be it for direct use of vegetable oils or for blends with diesel oil. The divergences can be explained by differences in the qualities of the oils used, trial conditions, the equipment used, the types of engines used, etc. Nevertheless, it has to be acknowledged that the differences observed between results from vegetable oil trials and diesel oil trials are not significant.

Some differences in performance between SVO and diesel oil are unanimously recognized: approximate 10% drop in power, deposits in the combustion chamber in direct-injection engines (all publications).

The disagreements mostly concern:

- Specific consumption (sometimes higher than for diesel oil, sometimes lower).
- Nature of pollutant emissions.
- Ignition delays (sometimes longer, sometimes the opposite).
- The causes of deposit formation.

3.4.2. Comparison between direct SVO and SVO in blends with diesel oil

The reason for using vegetable oil blends with diesel oil is to reduce viscosity to facilitate vegetable oil flow, spraying and atomization. Studies on the use of blends as engine fuel show that the performance is comparable to that of diesel oil with blends containing less than 30% vegetable oil [17,21,39,40]. In general, the pollutant emissions and performances obtained with blends fall between those for straight vegetable oils and pure diesel oil [13,17].

In terms of endurance, the performance of diesel engines running with blends containing a small proportion of vegetable oil (under 20%) is comparable to pure diesel oil. Only direct-injection diesel engines running with blends with a low vegetable oil content experience deposit formation in the combustion chamber, though it takes the deposits longer to form for a mixture with a low SVO content compared to direct SVO use.

3.4.3. Recommendations

Based on an analysis of the set of published works, a certain number of recommendations can be made for efficient use of SVOs directly or in blends with diesel oil in diesel engines:

- dual fuelling is recommended for whatever type of use without any trouble,
- SVOs should be used pure (100%) when the engine is running at least at 70% of its nominal load,
- in blends with diesel oil, SVO contents should not exceed 30% (without dual fuelling),
- injectors must be adjusted for fine fuel spraying.

The recommended mode of operation varies depending on the fuel used (SVO or blending):

- the blending option is interesting for industrial type applications (no need for modifications and adaptations of the engine).Care must be taken not to exceed 30% of oil in the blend,
- on the contrary, for community or village applications, the blending option is not recommended. Indeed the attempt by actors who use the engine to exceed 30% of the oil in the mixture is quite common. In this case the engine will run initially but deteriorates rapidly. The ideal solution is the dual fuelling.

4. General conclusion

Amongst biofuels, SVOs can be used to replace diesel oil, the main agricultural fuel, in diesel engines. They can be directly produced locally in a short supply chain and offer the extra fuel needed to increase agricultural production. They do not generate

undesirable waste, indeed their by-products can be used in agriculture and livestock production [62].

SVOs as fuel for diesel engines offer some considerable advantages [18]:

- they are produced in rural areas and can contribute to the local economy,
- they are biodegradable and they are renewable fuel with short carbon cycle period (1–2 years compared to millions of years for petroleum fuels) and are environmentally friendly,
- they have physical and combustion characteristics similar to those of pure diesel oil,
- they have a low sulphur content compared to pure diesel oil,
- they have flash point higher than that of diesel oil thus are safer for use.

The purpose of this paper was to bring together all the knowledge available on the production and use of fuel SVOs. The following points were covered:

- impact of the physico-chemical characteristics of fuel SVOs,
- impact of production parameters on SVO quality, and lastly,
- two types of SVO use in diesel engines: duel fuelling and blending.

Natural fuel oil can be produced using small-scale tools or industrial tools existing in the food sector. Quality demands are less strict and cheaper than in food production. They mainly concern pressing, filtration and storage [62]. Currently, it is important to acknowledge the lack of quality standards for oils as fuel (Cirad and 2iE are working on it). It is widely recognized in literature that the oil must be filtered to 5 μm with a H_2O content of 750 and 30 ppm phosphorus.

SVOs are fuels for which the parameters affecting final oil quality have to be mastered, including storage conditions, seed quality and moisture content, ambient temperature, seed preparation prior to pressing (cleaning and any preheating), extraction (which needs to be carried out with a minimum of shear and as low a temperature as possible), but also and predominantly, filtration quality (equipment, procedures, etc.) and storage quality.

This bibliographical study revealed that SVO use in diesel engines calls for. Upstream adaptations (dual fuelling, blending, preheating, etc.) or modifications to the engine (feed pump, fuel filter, injection pump and injector) or inside the engine combustion chamber (piston modification).

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